

January/February 2016

Science & Technology

REVIEW

TARGETING ***EXTREME PHYSICS***

Also in this issue:

Three Livermore Teams Win R&D 100 Awards
Award Finalists Improve Existing Technologies
Doped Glass Enhances Light Absorption

About the Cover

The National Ignition Facility (NIF), the world's most energetic laser, is an advanced capability designed to help researchers better understand the behavior of materials under extreme pressures and temperatures. As the article beginning on p. 4 describes, NIF experiments rely on a wide variety of targets, all of which have intricate assemblies of extremely small parts. NIF's millimeter-scale targets, combined with associated laser pulse shapes and a vast array of diagnostics, make possible breakthrough research for stockpile stewardship; inertial confinement fusion; high-energy-density physics; and discovery science, which includes astrophysics and materials science. On the cover, General Atomics collaborator Joseph Florio inspects a precision target prior to an experiment.



Cover design: Acen Datuin; Photography: Jason Laurea

About S&TR

At Lawrence Livermore National Laboratory, we focus on science and technology research to ensure our nation's security. We also apply that expertise to solve other important national problems in energy, bioscience, and the environment. *Science & Technology Review* is published eight times a year to communicate, to a broad audience, the Laboratory's scientific and technological accomplishments in fulfilling its primary missions. The publication's goal is to help readers understand these accomplishments and appreciate their value to the individual citizen, the nation, and the world.

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Prepared by LLNL under contract
DE-AC52-07NA27344

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S&TR, a Director's Office publication, is produced by the Technical Information Department under the direction of the Office of Planning and Special Studies.

S&TR is available on the Web at str.llnl.gov

Printed in the United States of America

Available from
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road
Springfield, Virginia 22161

UCRL-TR-52000-16-1/2
Distribution Category UC-99
January/February 2016

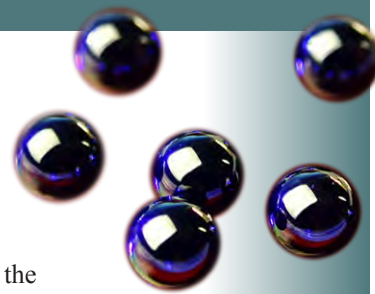
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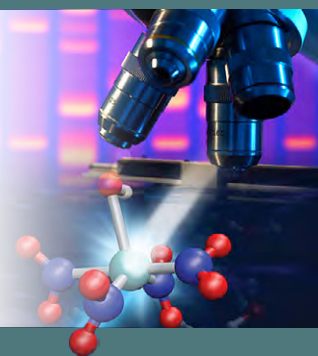
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Marginal Soil Can Make for Good Biofuel Crops

New research by Lawrence Livermore, the University of California at Berkeley, the University of Oklahoma, Lawrence Berkeley National Laboratory, and the Samuel Roberts Noble Foundation is studying whether cultivation of switchgrass (*Panicum virgatum*)—a native North American prairie grass with broad adaptability and minimal nutritional needs—could enhance key ecosystem services such as carbon sequestration, soil fertility, and biodiversity. Switchgrass (shown at bottom of page) is one of the most promising bioenergy crops in the United States, with potential to provide high-yield biomass on marginal soils unsuitable for traditional agricultural crops.

According to Jennifer Pett-Ridge, co-principal investigator of the project, roughly 11 percent of the U.S. mainland is composed of “marginal lands” and represents an untapped agronomic resource well suited to switchgrass’ deep, extensive root-growth architecture. “This project will provide unprecedented insight into plant–microbial interactions that enable success under environmental stress, and will provide a model for other biology studies of plant–microbial interactions,” says Pett-Ridge.

Understanding the biochemical and genomic basis of beneficial plant–microbial interactions is a challenge for agriculture, forestry, and invasive species management. The Laboratory will receive approximately \$1.6 million over five years from the Department of Energy’s Office of Biological and Environmental Research to conduct the study. To understand the relationships between switchgrass productivity and environmental effects in marginal soils, the team will analyze plant–microbial interactions within cultivated switchgrass growing under a range of resource limitations, and will document how these interactions contribute to desired ecosystem services.

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Rare-Earth Elements Advance Unified Theory

A team of scientists from the Laboratory and the School of Physics at the University of New South Wales in Australia recently demonstrated that the properties that make rare-earth elements useful for a variety of applications also make them great probes of physics beyond the Standard Model. The research appeared in the October 14, 2015, edition of *Physical Review A*.

The 17 rare-earth elements occupy the row above the actinides in the periodic table. Despite their name, rare-earth elements (with the exception of promethium) are found in relatively high concentrations across the globe. However, because of their geochemical properties, they seldom occur in easily exploitable deposits. These elements are essential for American competitiveness in the clean-energy industry because they are used in many devices important to a high-tech economy and national security, including computer components, high-power magnets, wind turbines, mobile phones, solar panels, superconductors, and the National Ignition Facility’s neodymium-glass laser amplifiers.

According to Livermore’s Michael Hohensee, who led the research team, rare-earth elements make great magnets in part because they have an incompletely filled 4f orbital that can hold a large number of unpaired electrons, which have larger orbital angular momentum than in other atomic orbitals. At the same time, these electrons are protected from their surroundings by other, paired electrons, that form a shield around them. Consequently, rare-earth elements maintain the unusual properties of their 4f orbitals when mixed into a piece of glass or crystal that can then be used in laser applications. “Thanks to their shielded status, and large orbital angular momentum, electrons in the 4f orbital can also be used to perform the electronic equivalent of a Michelson–Morley experiment that would be more sensitive than any other yet performed, helping to validate or rule out proposed theories that unify gravity and particle physics,” says Hohensee. The Michelson–Morley experiment forms one of the fundamental test of special relativity theory.

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Laboratory Scientists Discover Five New Nuclei

In a paper published in the September 2, 2015, edition of *Physics Letters B*, Lawrence Livermore scientists, in conjunction with international researchers, detail five newly discovered atomic nuclei to be added to the chart of nuclides. These exotic nuclei are one isotope each of heavy elements berkelium, neptunium, and uranium and two isotopes of the element americium. The study focuses on developing new methods of synthesis for superheavy elements.

For the experiment, the scientists, who included Livermore’s Dawn Shaughnessy, Ken Moody, Roger Henderson, and Mark Stoyer, shot accelerated calcium nuclei at a 300-nanometer-thick foil of curium. In the collisions studied, the atomic nuclei of the two elements touched and formed a compound system for an extremely short time. Before the compound system could break apart again, after about a sextillionth of a second, the two nuclei exchanged a number of their nuclear building blocks—protons and neutrons.

The isotopes of berkelium, neptunium, uranium, and americium discovered were created as the end products of such collisions. They are unstable and decay after a few milliseconds or seconds, depending on the isotope. All of the resulting decay products can be separated and analyzed using special filters composed of electrical and magnetic fields. The scientists used all of the decay products detected to identify the new isotopes, which have fewer neutrons and are lighter than the previously known isotopes of the respective elements. “These results push what we know about nuclear structure to the extreme, neutron-deficient end of the chart of the nuclides,” says Shaughnessy. “When you realize that naturally occurring uranium has 146 neutrons and this new isotope only has 124 neutrons, it shows how much more we still have yet to learn about nuclear structure and the forces that hold the nucleus together.”

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Tiny Targets Enable Breakthrough Scientific Discoveries

THE 192-beam National Ignition Facility (NIF), the world's largest and most energetic laser, is also one of the most productive scientific research facilities in existence. NIF experiments create temperatures of 100 million degrees and pressures 100 billion times that of Earth's atmosphere. Every experiment requires a millimeter-scale target made of various precision, fragile components. Each target has been carefully designed by teams of scientists and engineers, manufactured to extraordinary tolerances by talented technicians, assembled in clean rooms rivaling those in semiconductor plants, and inspected with microscopes and other fine-scale tools.

The feature article beginning on p. 4 describes the challenging materials science and engineering associated with fabricating NIF targets. Five different targets are discussed that illustrate the Laboratory's wide-ranging experimental physics program conducted at NIF in the areas of inertial confinement fusion (ICF), materials strength, materials structure, radiation transport, and astrophysics. These five examples represent the culmination of more than three decades of laser target design and fabrication at Livermore.

All of these targets are engineered to re-create the physics regimes our investigators require to probe matter in extreme environments. Indeed, NIF's suite of capabilities—including diagnostics, laser attributes, staff expertise, as well as targets—have evolved in response to the extreme physics necessary for our investigators' research. As experiments at NIF have matured over the past several years, so have the complexities of target components and the advanced materials of which they are made. Target materials include metals, polymers, gases, and low-density aerogel foams. We depend on a team of highly skilled engineers, scientists, machinists, and technicians to develop the means to fabricate and assemble them into exquisite, minuscule objects.

The intense temperature and pressure conditions targets encounter during experiments make results highly susceptible to any manufacturing imperfections. All targets must meet precise specifications for such attributes as dimensionality, density, and surface finish. For example, some components must be machined to an accuracy of 1 micrometer with surface features no larger than approximately 10 nanometers. As our experimental

diagnostics improve, greater demand exists for precision in target fabrication, assembly, and metrology.

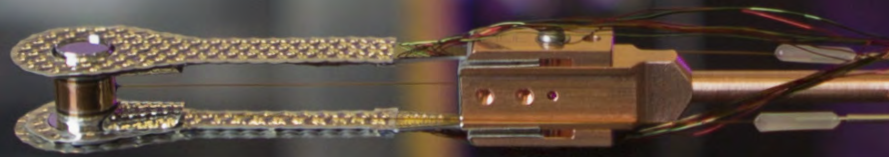
Cryogenic ICF targets are among the most complicated in current use. At their core is a 2-millimeter-diameter plastic or diamond capsule that is filled with the hydrogen isotopes deuterium and tritium. The capsule is centered inside an approximately 9-millimeter-high by 5-millimeter-wide hohlraum cylinder. A remarkably thin polymer "tent" holds the fuel capsule in place. We are working on innovative methods to replace this tent because experiments have shown it interferes with the smooth compression of the fuel capsule by the x rays generated when laser beams strike the hohlraum's inner walls.

A completely different type of target, designed to re-create the young cluster of stars called the Eagle Nebula, is particularly illustrative of NIF's extraordinary capabilities. The Eagle Nebula stretches light years across in deep space, and yet we can reproduce the same physics regimes with an extremely small target. I find our ability to duplicate celestial phenomena thousands of light years away using NIF an impressive feat of science. By microencapsulating the physics of the life and death of stars, planets, and galaxies, we learn more about the physical processes driving our universe.

We have established an ambitious production goal of nearly 500 targets for the 2016 fiscal year to meet an ever-increasing shot rate. Along with this rise in production, we are striving to become more agile so that we can respond faster to the demands of new target design concepts and the novel materials they may require. Together with our partners General Atomics and Schafer Corporation, we continue to improve production processes. For example, we are automating some manufacturing, assembly, and inspection activities. In this way, we can manufacture multiple copies of the same target design more consistently, which is critical to building experimental data sets. Toward boosting efficiency, we are also consolidating the footprint of our target assembly areas. With these improvements and further advances in target design, we look forward to the important scientific discoveries that may be possible using NIF.

■ Jeff Wisoff is principal associate director for NIF and Photon Science.

A Growing Family of Targets for the NATIONAL IGNITION FACILITY



Remarkably tiny and precisely manufactured targets are enabling breakthrough physics and materials research.

In the world of experimental physics, the National Ignition Facility (NIF) is a modern marvel—an advanced tool designed to help researchers better understand the behavior of materials under extreme pressures and temperatures. The world’s most energetic laser, NIF creates temperatures greater than those of the Sun and pressures 100 billion times Earth’s atmosphere, conditions similar to those in stars and detonating nuclear weapons.

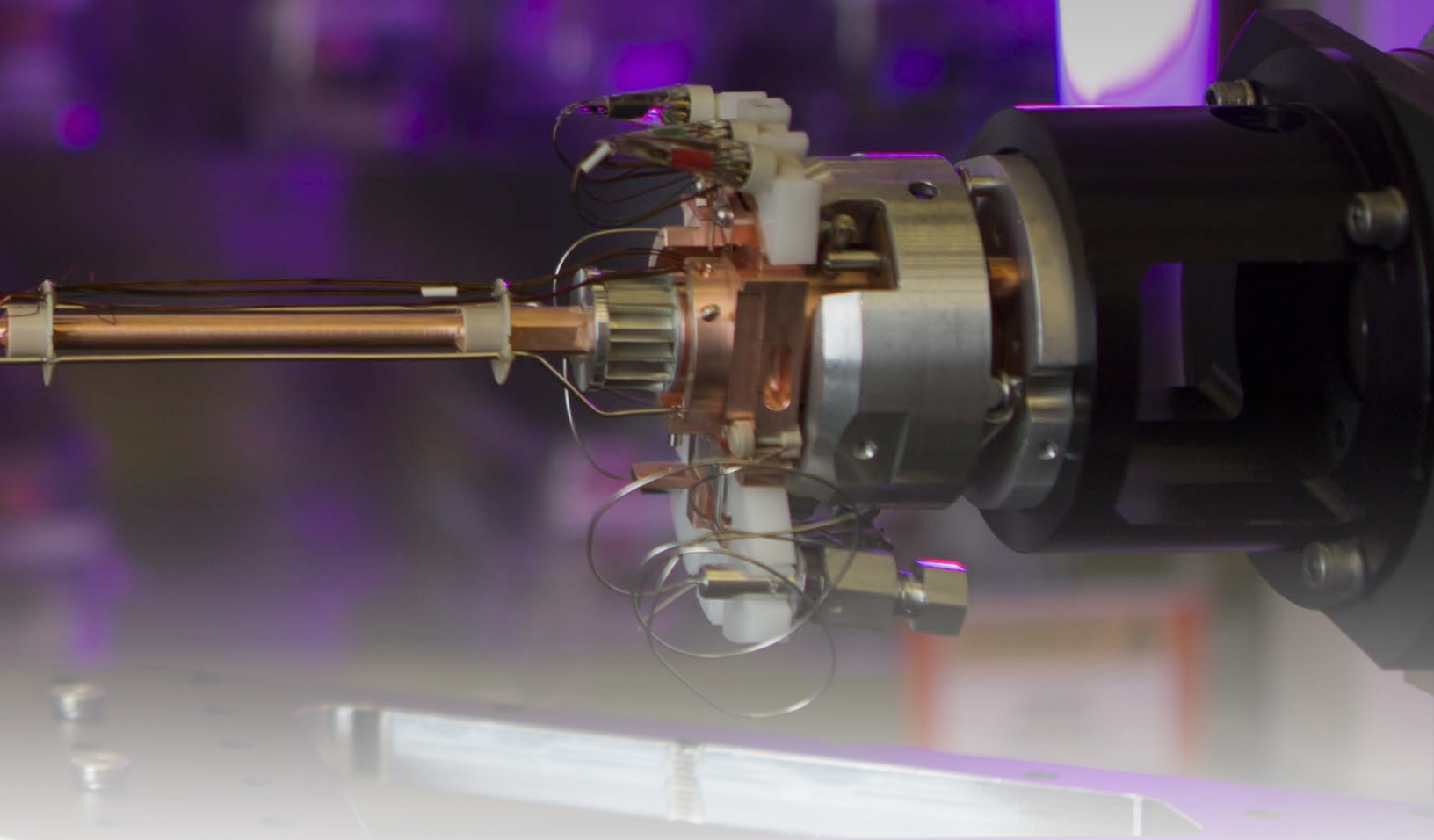
NIF is the paramount experimental facility in the National Nuclear Security Administration’s Stockpile Stewardship Program to ensure the continuing

safety, security, and effectiveness of the nation’s nuclear weapons. (See *S&TR*, July/August 2015, pp. 6–14). NIF’s millimeter-scale targets, combined with associated laser pulse shapes and a vast array of diagnostics (together called a platform) also make possible breakthrough research in inertial confinement fusion (ICF), high-energy-density (HED) physics, and discovery science (in areas such as astrophysics and materials science).

NIF experiments rely on a wide variety of targets, all of which have intricate assemblies of extremely small parts. Designing, machining,

and assembling these parts with micromanipulators into precisely manufactured targets requires a complex interplay among target designers, physicists, materials scientists, chemists, engineers, and technicians.

The physics package contains the main experimental components of every NIF target and may include an ablator to initiate a specific ramp of pressure, a “reservoir” of different materials to shape a compression pulse, a backlighter that creates a beam of diagnostic x rays when illuminated by laser light, a cylinder called a hohlraum to convert laser light to x rays, and a material under



investigation. However, the complete target assembly also contains shields to protect the NIF beamlines from potentially destructive back-reflected light and debris created during the shot; stalks to hold parts rigidly in position; and features to aid the proper alignment of laser beams, target, and diagnostics for an experiment.

Target components are produced by the Laboratory; General Atomics of San Diego, California; and Schafer Corporation of Livermore, California. Assembly and inspection teams are composed of experts from all three entities, and construction of the final

target is conducted at the Laboratory. “Our targets are fragile, so we want them assembled close to NIF,” explains target fabrication manager and physicist Abbas Nikroo. Most targets are assembled in a 334-square-meter Class 100 clean room, which limits dust to no more than 100 particles 0.5 micrometers or larger per 0.28 cubic meters of air.

About 40 percent of targets are designed for ICF experiments, another 40 percent are for HED experiments, and the rest are for discovery science and various national security programs. To increase production efficiency, engineers strive to take the artisan aspect out of

manufacturing as much as possible. “We have streamlined design and production of ignition targets so the process is more like plug and play,” says Nikroo.

Approximately 430 targets were manufactured from September 2014 to October 2015, and at least 190 of these had unique fabrication requirements. In contrast to standardized ICF target designs, HED target geometries and materials are always changing to meet specific experimental goals. Low-density foams with complex properties are a common feature in HED targets. By varying foam densities and compositions, target designers tailor the desired physics

characteristics for each experiment. Developing novel foams of uniformly high quality that can be machined and assembled into a target is a significant manufacturing challenge.

Meeting Precise Specifications

The small-scale phenomena and extreme conditions targets encounter during experiments make the results highly susceptible to any manufacturing imperfections. Therefore, all targets must meet precise specifications for factors such as density, concentricity, thickness, uniformity, shape, roughness, internal microstructure, location of dopants, accuracy of joints and parts, and surface finish. For example, target components are typically machined to an accuracy of 1 micrometer (millionth of a meter), while some surface features cannot exceed 20 nanometers (billionth of a meter).

Many fabrication techniques, materials, and tools are derived from other industries. Chemical engineer Alex Hamza notes that target assembly processes include techniques borrowed from in vitro fertilization, in which microscopic procedures are performed on a human cell measuring about 10 micrometers in diameter, the same size as many features found on NIF targets. At the same time, new fabrication, measurement, handling, and inspection methods are developed in-house. “We can’t use tweezers because they would damage the fragile parts,” says mechanical engineer Becky Butlin, who supervises most assembly operations. Instead, technicians use pen-like devices that hold onto tiny parts with a gentle vacuum force.

Components are made from foams, plastics, crystals, gases, and metals. Fabrication capabilities include single-point diamond turning lathes, precision milling and grinding, laser micromachining, polishing, lithography, chemical vapor deposition, electro-deposition, atomic layer deposition,



A target fabrication technician uses an optical coordinate measuring machine to align a capsule inside a hohlraum for an inertial-confinement-fusion (ICF) target.

and implantation of metal impurities called dopants.

At every assembly step, workers inspect components using nondestructive methods, such as various types of microscopy, radiography, interferometry, and spectroscopy, as well as optical coordinate measurement and x-ray fluorescence to ensure precise target specifications are met.

Butlin notes that recruiting qualified staff for target fabrication is a challenge. “We look for people who have clean room and microscope experience and mechanical aptitude, but most skills must be learned on the job,” she says. To streamline the most delicate and time-consuming tasks, precision robotic stations have been installed.

Birth of a Target

To turn a sketch or idea for a new target into reality, experimenters must first discuss with target engineers the overall concept, the necessary components and materials, required specifications and parts tolerances, and

the data they want to obtain. Nikroo says that early consultation is critical because materials availability as well as target fabrication and assembly challenges may affect the fabrication timeline. Target engineers determine the feasibility of fabricating and assembling the components. Importantly, Nikroo notes, “Target engineers know the limits of their manufacturing tools.”

Over several weeks, experimenters collaborate with representatives from target engineering and NIF laser alignment and operations to uncover and resolve any physics, safety, and contaminant issues. The cleanliness of NIF target assemblies must be rigorously controlled to prevent laser optics damage from plasma and debris and to avoid contaminating sensitive coatings on lenses and other optics. High-fidelity computer simulations are sometimes conducted to determine the likelihood that any debris will be generated from a new target.

Five remarkably different targets exemplify the wide range of materials

and geometries a NIF target may have and the distinct physics areas they are created to address. These targets include those to determine materials strength, investigate the physics of fusion reactions, research the early stages of star formation, determine materials structures under high pressure through x-ray diffraction, and measure x-ray transmission in three dimensions.

Metals Under Pressure

A material's strength determines to what extent the material deforms when it is stretched or compressed. NIF experiments are designed to measure strength at extremely high pressures without significantly increasing the temperature of the material being tested. About a dozen such experiments are conducted yearly at pressures never achieved in a laboratory until NIF began operation.

Mechanical engineer Angela Cook notes that strength and diffraction experiments (see pp. 10–11) complement each other. Both types of tests examine materials subjected to tens of millions of Earth atmospheres. The current strength-platform design was finalized after experiments were conducted first at the University of Rochester's Omega Laser Facility and then at NIF. Current

targets have a production cycle of about three months, and, owing to changing experimental needs, are made only three at a time.

The target assembly features a hohlraum 9 millimeters in diameter by 14 millimeters long made from a thin film of epoxy coated inside with a layer of gold. Positioned directly over a side hole in the hohlraum is a 2-millimeter-thick, multilayered physics package containing a reservoir of five different materials, including two foams—each of a different density and diamond-turned to exact dimensions and surface finish—and an enclosed metal sample. Laser light enters the top and bottom of the hohlraum, creating x rays that ablate the reservoir and produce a pressure wave of plasma. The pressure wave unloads across a vacuum gap and through two x-ray shields of gold and plastic before impacting the metal sample. To achieve high pressures without melting or shocking the target, the reservoir is designed to carefully shape the pressure wave such that the pressure is slowly ramped up over a period of nanoseconds.

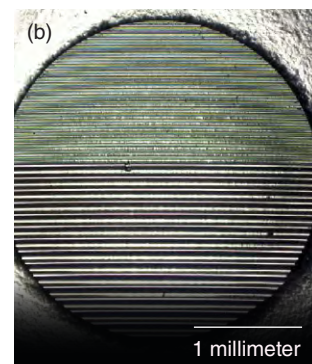
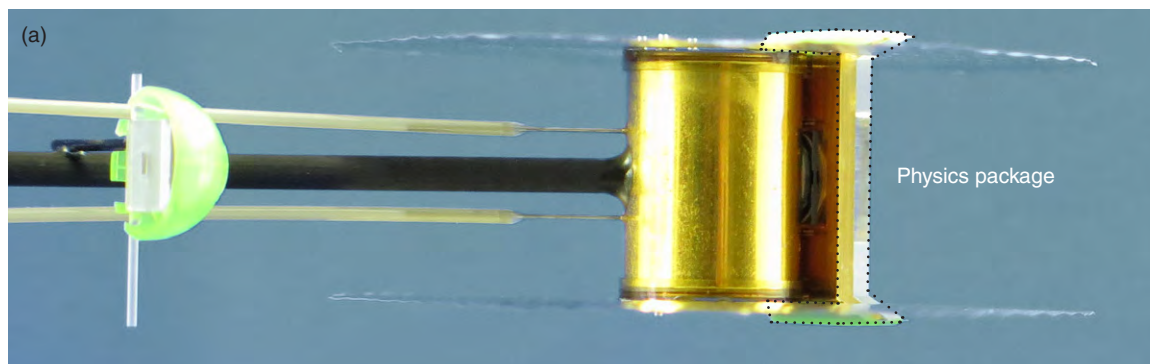
The metal samples were meticulously imprinted with two-dimensional sine-wave patterns of 1-micrometer amplitude (height) and wavelengths

between 50 and 75 micrometers.

Materials scientist Kerri Blobaum's team adapted a pressing technique used by the U.S. Mint to precisely stamp or "coin" the microscopic ripples into metals (see *S&TR*, September 2015, pp. 21–23). During the experiment, the imprinted ripples grow when they experience compressive pressure from the shocked reservoir as it pushes against the target. "The ripples grow at a slower rate when material strength is high," explains Cook.

About 50 to 80 nanoseconds after the initial laser pulse causes the reservoir to apply pressure to the sine-wave sample, a second laser pulse strikes a backlighter (a thin film of silver or zirconium), creating an x-ray radiography source. The backlighter's x rays are focused with a collimator and used to capture an image of the growing ripples with an x-ray imaging diagnostic.

The physics and target teams are currently developing a second experimental platform that will use NIF's Advanced Radiographic Capability (ARC), the world's highest energy short-pulse laser. In this new platform, the ARC beam strikes a backlighter foil that produces a higher energy x-ray source for improved x-ray imaging of the material under study.



(a) The target for a strength experiment features a 9-by-14-millimeter hohlraum. Positioned over a side hole in the hohlraum is a 2-millimeter-thick, multilayered physics package containing a reservoir of five different materials, gold and plastic x-ray shields, and a sample of the metal of interest. (b) The metal sample is imprinted under a microscope with two-dimensional sine-wave patterns. The imprinted ripples grow when they experience the pressure wave generated in the experiment.

Efforts Toward Ignition

In ICF experiments, laser beams strike the inside walls of a hohlraum. The resulting x rays compress a 2-millimeter-diameter capsule containing deuterium and tritium (D–T) fuel. ICF targets are extremely smooth and fabricated from plastic polymer, diamond (high-density carbon), or beryllium. The capsules may also contain internal layers with dopants that increase x-ray absorption. Precise control over dopant concentrations and uniformity is a materials challenge.

The capsule is suspended at the center of a gold hohlraum, which is approximately 30 micrometers thick, 9 millimeters high by 5 millimeters in diameter, and built in two halves. New experimental designs have increased the size of the hohlraum for more uniform

implosion, while other target designs feature subscale versions. “Shots using smaller scale hohlraums require less laser energy so they cause less optics damage but still provide meaningful data,” explains chemist Michael Stadermann, group leader of science and technology for target fabrication. An alternative experimental hohlraum features a liner of depleted uranium for higher conversion efficiency of laser light to x rays. Livermore scientists have also pioneered a system to supply D–T gas into the capsule through a fill hole less than 5 micrometers across, characterize the resulting cryogenic inner D–T layer, and then maintain the entire target package below 20 kelvin.

The capsule is supported in the hohlraum by a very thin plastic film

called a tent. Recent experiments have shown that this tent causes a perturbation during the implosion. “The perturbation seems to scale with tent thickness for some pulse shapes, but it may not be possible to make a tent thin enough to eliminate the problem,” says Stadermann. Thus, despite having reduced tent thickness from 300 to 30 nanometers, the team is looking at other support methods.

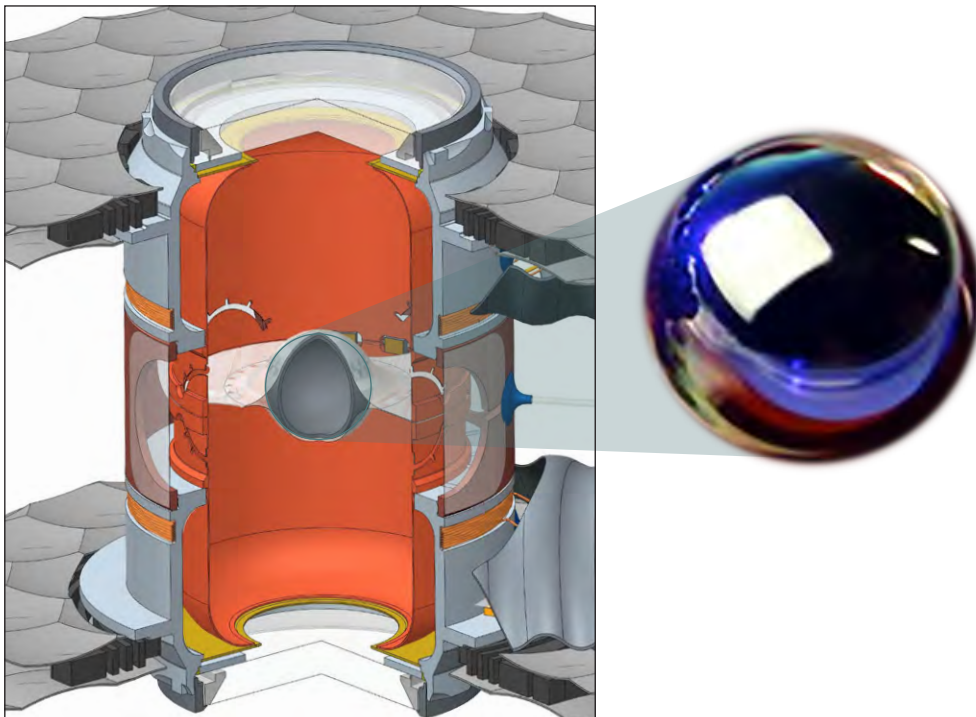
ICF targets are designed to generate fusion reactions with the eventual goal of ignition—where energy output is equal to or greater than the amount of laser energy incident on the target. Other targets are designed to diagnose experimental parameters of imploding capsules. These specialized targets provide information on shock timing, capsule implosion shape, implosion velocity, and the extent of colder D–T fuel mixing with the fuel core “hot spot.”

The fuel capsule requires a precise spherical shape with surfaces smoothed to approximately 1 nanometer. Various metrology tools ensure that capsule specifications are met. For example, atomic force microscopy checks capsule shape and roughness. Phase-shifting diffractive interferometry looks for isolated defects, and precision radiography confirms capsule uniformity.

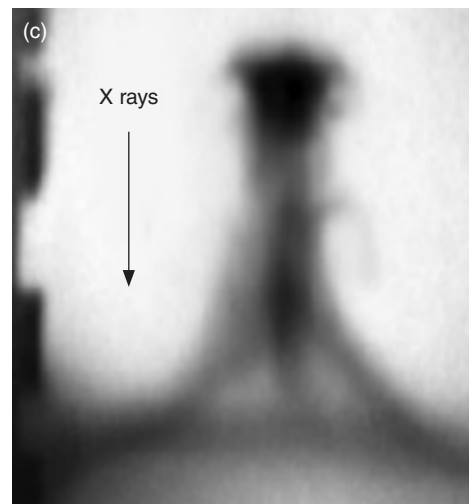
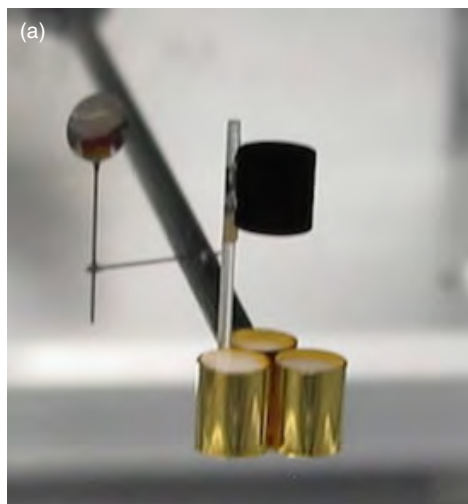
Robots have automated some time-intensive target assembly and characterization processes. “Robots save training time and improve the quality and uniformity of the target,” says Stadermann. One robot installs the tents, and another inserts the hohlraum into the thermomechanical package that will keep ICF capsules extremely cold. Together, these systems save about eight hours of fabrication time per target. A new automatic proofing station for testing the cryogenic targets promises to save an additional eight hours per target.

Re-Creating Eagle Nebulae

In 1995, the Hubble Space Telescope captured the famous images of the



In ICF experiments, laser beams strike the inside walls of a hohlraum 9 millimeters high by 5 millimeters in diameter and built in two halves. The resulting x rays compress a 2-millimeter-diameter capsule containing deuterium and tritium fuel. The capsule is suspended in the center of the hohlraum with remarkably thin polymer tents. (inset) ICF target capsules are extremely smooth and fabricated from plastic polymer, beryllium, or diamond (high-density carbon).



(a) The TriStar target has three drive hohlraums, a layered foam physics package, and a radiography backlighter. The hohlraums are driven for 10 nanoseconds each in series, giving a total x-ray output lasting 30 nanoseconds. The TriStar target is designed to investigate the origin and dynamics of pillar formation such as (b) those captured from within the famous Eagle Nebula. A team of Livermore physicists led by Jave Kane and David Martinez succeeded for the first time in (c) creating pillar structures in a laboratory using a layered foam target. (Hubble image courtesy of NASA/European Space Agency/Hubble Heritage Team [Space Telescope Science Institute/Association of Universities for Research in Astronomy]).

“Pillars of Creation” in the Eagle Nebula. Twenty years later to the day, NIF researchers began conducting experiments aimed at investigating pillar formation. The team is studying whether such pillars could form from a dense cloud core in the presence of a process called ablative stabilization, which prevents the growth of traditional Rayleigh–Taylor instabilities.

In the experiments, the NIF laser is fired at a target nicknamed TriStar or QuadStar—three or four hohlraums joined together that mimic the cluster of massive stars illuminating the Eagle Nebula. To extend the duration of the high-pressure drive, the laser fires a 10-nanosecond pulse of ultraviolet light into the bottom of each hohlraum in sequence. The hohlraums measure 3 millimeters in diameter by 4 millimeters long and are driven for 10 nanoseconds each. “We want the experiment to run like a Gatling gun,” says Russell Wallace, leader of the group that fabricates targets for discovery science.

The hohlraums re-radiate the light energy as x-ray pulses. These pulses then drive a shock into a layered foam cylinder and create a miniature version of a pillar that is imaged using x-ray radiography. In this way, the x rays from the hohlraums mimic a cluster of stars illuminating the Eagle Nebula. In addition, some of the NIF laser beams are directed to a 25-micrometer-thick titanium backlighter. The beams hit the backlighter’s front side, generating x rays that illuminate the evolving foam plasma. A pinhole camera takes a single photograph, giving a snapshot of the evolution.

The experimental concept was tested over two years at the Omega Laser Facility. The NIF shots use larger targets and 20 times the laser energy than was possible with the Omega system. NIF is the only facility that can generate an x-ray source that is sufficiently intense, long-lasting, and directional to drive the desired flows.

Target physicists Jave Kane and David Martinez first brought Wallace a sketch

of a target with material designations and general component sizes. “They had the concept and we provided the details,” says Wallace. “It was a happy marriage. Target development is always an iterative process.” The team turned the sketch into detailed engineering drawings, including critical NIF alignment requirements. “NIF has only a limited ability to position the target and ensure the beams are correctly pointed,” he explains. For these targets, the glass rod that holds the foam cylinder also provides a key element used for aligning the target.

As part of the target design phase, the team had to examine the possibility that debris generated by the experiment could damage diagnostic instruments or optics. This process also involves resolving any issues with unconverted light, which can travel back up the beamline and damage optical components. Finally, the target design process clarifies the target subcomponents and the level of complexity required for their manufacture. The foam components had the most demanding requirements for

these targets but were successfully built using target technologies developed and refined over the years.

Tracking Radiation

Radiation transport, the flow of x rays through materials, is an important property used to validate supercomputer codes for stockpile stewardship as well as to understand the formation of stars and the heating of ICF capsules. With radiation transport targets, researchers investigate how high temperatures affect radiation flow through a material at the speed of sound and greater.

Historically, radiation transport experiments have measured flow in a two-dimensional geometry. However, current designs utilize a nested silica (silicon dioxide) and tantalum (an oxide of tantalum) hemispherical foam target to measure radiation flow in three dimensions. Three-dimensional measurements required new glass tube or “light pipe” diagnostics because traditional Velocity Interferometer System for Any Reflector (VISAR) diagnostics do not work in an arc geometry.

Mechanical engineer Danielle Doane says the challenges associated with these targets include synthesis of low-density foams and exact interference press fits. The target is a complex assembly of millimeter-scale parts with micrometer tolerances. The foam construction contains nested shells of 0.125-grams-per-cubic-centimeter tantalum only 0.10 millimeters thick. The middle silica foam has a density of 0.045 grams per cubic centimeter and is 0.64 millimeters thick. The inner tantalum foam has a density of 0.125 grams per cubic centimeter and a thickness varying from 0.15 to 0.35 millimeters.

The targets require about three months to build, including eight weeks for foam machining, which involves micromilling and diamond turning. The foams are machined on a 5-axis micromill with tool diameters down to 25 micrometers to produce a few hundred micrometer-level surface finish. The three different

nested foam layers are pushed together with an interference fit to attain an adhesive-free interface.

The foam subassembly is suspended with a tent inside a two-part hohlraum. Several light pipes are inserted at specific angles and positions to allow the transmission of x-ray signals from the target to diagnostics. Coated with gold on the inside, the light pipes are inserted using precision stages and view ports in the hohlraum for positioning accuracy. Final target fabrication involves gluing the nested foam assembly to a top washer, then gluing the bottom half of the hohlraum to the top half, and ultimately inserting the top light pipes.

During experiments, laser beams enter the hohlraum from underneath, strike its walls, and generate x rays that turn the foam to plasma. Instruments record the movement of radiation flowing out of the hohlraum. Radiation transport experiments using these targets were first conducted on the Z machine at Sandia National Laboratories and at the Omega Laser Facility. More than a dozen targets with slight variations have been tested at NIF.

Targets for Diffraction Studies

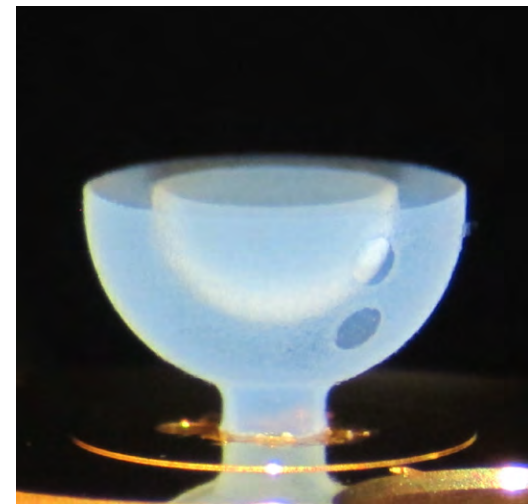
X-ray diffraction experiments probe the atomic structure of a material and thus identify its crystallographic phase (for example, face-centered or body-centered cubic—wherein the unit cell is cube-shaped). Specialized targets enable diffraction to be performed at extremely high pressures. Similar to strength experiments, diffraction studies require that the sample does not melt before the desired pressure is reached.

The experiments, called TARDIS (Target Diffraction In-Situ), are the first to include a NIF target and diagnostic on a single, integrated platform. The TARDIS target has a tantalum–tungsten alloy body, which houses the material sample; an x-ray backlighter mounted on a stalk; and a semicircular diagnostic cartridge containing image plates to capture the x-ray diffraction pattern.

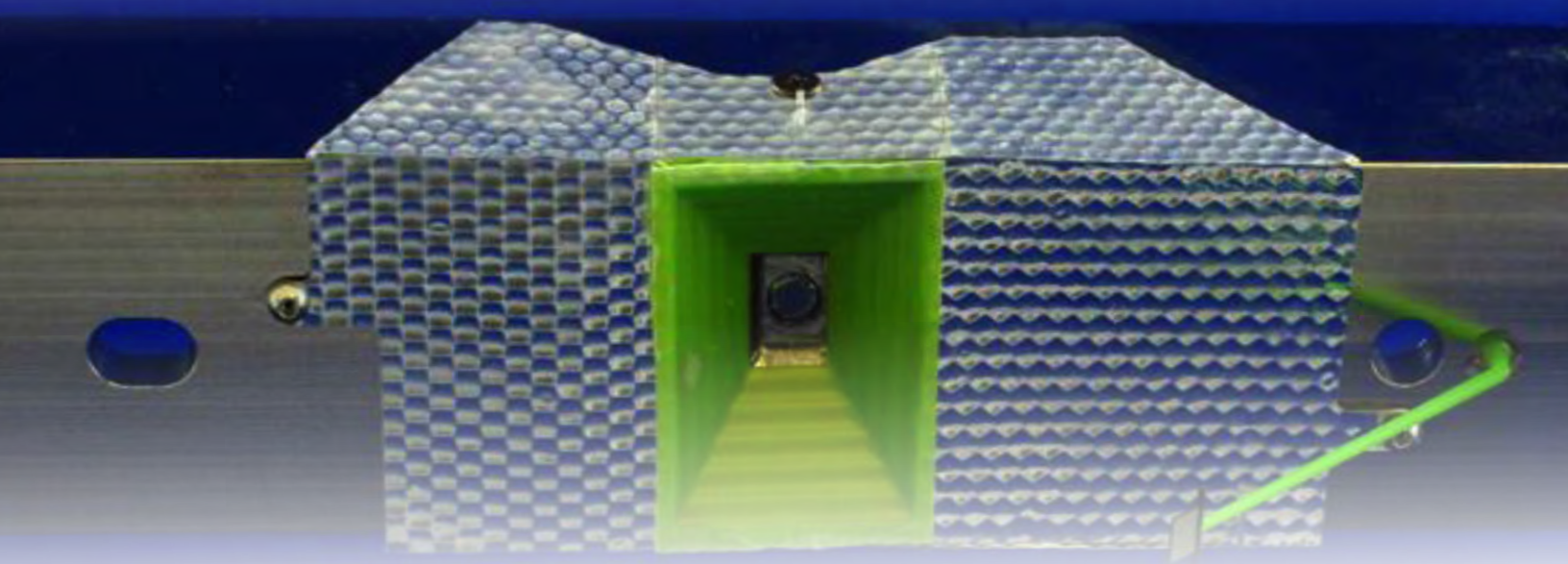
TARDIS experiments provide important information on the properties of materials at high pressures for stockpile stewardship applications. They are also designed to provide insight into phase changes, or structural transitions, that occur in materials under pressures comparable to those believed to exist in the cores of extrasolar planets many times more massive than Earth.

Each target contains a selected material some 4 to 8 micrometers thick and 2 to 3 millimeters in diameter sandwiched between two thin, single-crystal diamonds polished to exact specifications. A third diamond, coated with 2 micrometers of gold, is added to the sandwich, and the laser pulse strikes this diamond ablator.

As in strength experiments, an initial laser pulse generates pressure on the sample, and nanoseconds later, additional laser beams hit the backlighter (germanium on carbon) to generate diagnostic x rays. When the initial laser light strikes the diamond ablator, the sample is ramp-compressed and held at constant pressure



Radiation transport targets use nested, hemispherical foams to measure radiation flow in three dimensions. Glass tubes or “light pipes” are inserted through holes in the foam (seen here) to allow the transmission of x-ray signals from the target to diagnostics.



TARDIS (Target Diffraction In-Situ) experiments use x-ray diffraction to probe a material's atomic structure. The TARDIS package has a tantalum and tungsten target body, which houses the material sample; an x-ray source target mounted on a stalk; and a semicircular diagnostic cartridge containing image plates to capture the x-ray diffraction pattern of the sample.

and temperature. The diagnostic x rays are collimated by a 400-micrometer pinhole before being diffracted by atomic layers in the sample. The crystal diffraction lines are recorded onto image plates. The resulting diffraction pattern serves as a “fingerprint” for the crystallographic structure (phase) of the sample material under pressure.

The shots permit phase transitions to be studied in a wide variety of materials, such as carbon, iron, lead, tantalum, platinum, and uranium. Researchers control the pressure by the number of laser beams and the beams' energies. Approximately 30 experiments have been conducted, all at pressures greater than 1 megabar. Blobaum says, “We are learning about the structure of materials at conditions never previously achievable.”

The stringent thickness requirements for the targets' thin metal, diamond, and glue layers present significant manufacturing and inspection challenges. In response, target fabrication engineers have developed double-sided white-light interferometry to profile both sides of a part simultaneously and ensure it meets specifications. “We want the laser drive to be planar, so the metal and diamond layers

must be uniformly flat and parallel,” says Blobaum. In addition, alignment features on the TARDIS assembly help to precisely position the laser beams onto the sample.

Meeting Increasing Demand

As NIF's shot rate has increased, so too has the demand for targets. Despite the challenges involved in designing, manufacturing, and testing custom-made, precision-engineered targets, the fabrication and assembly teams are satisfying the need, with annual production predicted to grow from 430 to 480.

Nikroo notes that engineers have established faster fabrication and assembly methods, including modular and batch processing to speed deliveries and reduce nonuniformities. “We are making a big push to reduce the hours it takes to assemble a target,” says Butlin. Installing robotics into the assembly process is part of this effort.

The target fabrication team is also researching innovative techniques to position the D–T capsule in the center of the hohlraum without the thin polymer tent for ICF experiments. Other challenges with ICF targets include fabricating

depleted uranium hohlraums without gold liners, adding a silicon dopant to diamond capsules without creating excessive levels of silicon carbide, and avoiding nonuniform oxygen uptake in fuel capsules. With an eye on increasing data and extending experimental regimes, engineers are beginning to design double backlighters, which would capture two experiments' worth of data in a single target shot. With demand for NIF and its targets growing, experimentalists rise to the challenge of designing new and improved targets as scientists, engineers, and technicians endeavor to efficiently make them.

—Arnie Heller

Key Words: Advanced Radiographic Capability (ARC), backlighter, diffraction, Eagle Nebula, foam, high-energy-density (HED) physics, hohlraum, inertial confinement fusion (ICF), materials science, National Ignition Facility (NIF), Omega Laser Facility, radiation transport, ramp compression, TARDIS (Target Diffraction In-Situ), Velocity Interferometer System for Any Reflector (VISAR), Z machine.

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Improving Engine Designs with an Ultrafast Code

In pursuing ways to reduce pollution and conserve energy resources, researchers have begun designing more advanced, environmentally friendly engines for transportation. To better understand the chemistry of combustion for developing higher power efficiency, lower emission engines, engineers and designers rely on computer codes that can simulate and resolve thousands of intermediate chemical species. This process is critical for accurately predicting the ignition properties and pollutant emissions (nitrogen oxides and soot) for commercial combustion applications.

The complex interactions of intermediate chemical species can involve tens of thousands of reaction pathways. Consequently, even with high-performance computing systems, existing codes can require nearly a day to resolve a few seconds of reactions in a simplified simulation of gasoline combustion, thus limiting their usefulness in the engine-design process.

Livermore engineers Matthew McNenly and Russell Whitesides have developed an innovative computational method that significantly speeds up modeling the behavior of chemical systems. A 2015 R&D 100 Award-winning technology, the Zero-Order Reaction Kinetics (Zero-RK) software package simulates chemically reacting systems in a computationally efficient

manner. “The Zero-RK solver allows orders-of-magnitude faster simulation of these systems than is currently available with other software packages but still maintains the accuracy of the results,” says McNenly. “The reduction in time-to-solution will be a huge benefit for those designing next-generation engines based on conventional fuels and newer biofuels, giving them insight into the chemistry of fuel reactions and producing results in days instead of months or years.”

Simulating Chemistry in Motion

Zero-RK calculates the thermo-physical properties, reaction-rate coefficients, and production rates necessary to simulate the evolution of species in a chemically reacting system. Species are the molecules representing the initial reactants, final products, and stable and unstable intermediates. In a natural gas engine, for example, the methane fuel reacts with oxygen to form the products water and carbon dioxide. This process can be modeled by a single global reaction, but greater accuracy is achieved by resolving the intermediate species that are formed during the fuel conversion—including stable ones such as carbon monoxide, formaldehyde, and hydrogen peroxide, and highly reactive radical species such as atomic hydrogen, atomic oxygen, and the hydroxyl radical.

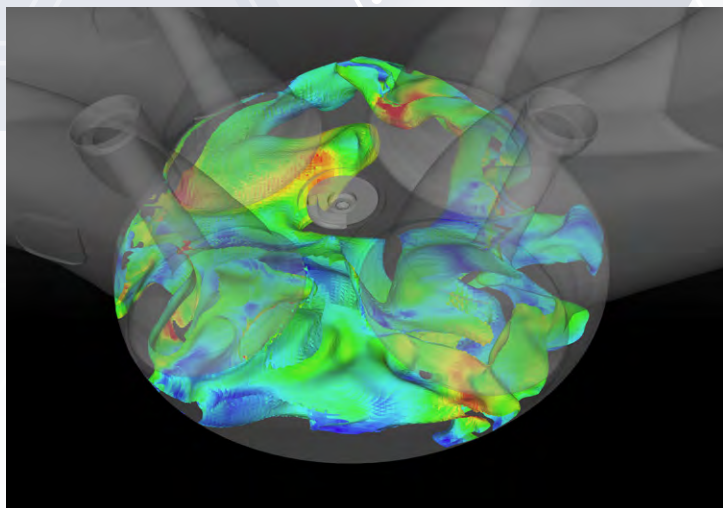
Modeling such detailed fuel chemistry for transportation fuels has been limited in commercial combustor design because of the prohibitive computational cost. Zero-RK directly addresses this challenge by allowing design calculations to use more than 10 times the number of intermediate chemical species for the same computational cost as the best commercial solver. “In working with industrial representatives, we recognized that most companies do not possess or have access to the high-performance computing resources we have here at the Laboratory,” says McNenly. “We therefore concentrated on ways to make our algorithms more efficient, and took advantage of memory cache and vector arithmetic capabilities present in modern computing processors, so that Zero-RK can be sized to run on the workstations or small computing clusters typically available in industry.”

More Speed, Maintained Fidelity

The fundamental advance of Zero-RK is a numerical approach called sparse adaptive preconditioning (SAP). The SAP strategy uses iterative, nonlinear solvers to determine the future

Livermore codevelopers of the Zero-Order Reaction Kinetics (Zero-RK) software package: (from left) Matthew McNenly and Russell Whitesides.





The local flame propagation speed in a gasoline combustion engine was simulated using Zero-RK as a plug-in to the computational fluid dynamics software ConvergeCFD.

composition of a chemically reacting system. The solvers first make an educated “guess” at the solution, which is then checked by the user for accuracy. Successive refinements to the solution are then made to improve the accuracy until the user is satisfied with the quality of the result.

The key to the process is the creation of solution refinements. McNenly says, “Typically, these refinements resolve the dependencies of the individual chemical species with one another, creating a dense network of connectivity, similar to how different cables are run to a home for various technologies such as televisions, computers, and phones. The SAP approach determines the most important connections in the chemical network to create one with fewer connections, similar to a wireless router. This leaner, or sparser, network retains enough key features of the system to still make continuous refinements but at a much faster compute speed.” In addition, when solving for reacting systems involving large numbers of species, the SAP strategy solves for the future chemical composition of a system without any loss of accuracy. This approach contrasts with competing software packages that commonly use species-reduction techniques, in which species deemed “unimportant” to the solution of interest are removed to lower the simulation cost.

Zero-RK also incorporates efficient algorithms for evaluating species’ thermo-physical functions and chemical reaction rates. When coupled with sophisticated computational fluid dynamics

(CFD) packages such as ConvergeCFD—developed by Convergent Science, Inc.—Zero-RK-based models can reduce the cost of chemistry simulations by a factor of seven for transportation fuels. The increased efficiency also allows combustion design engineers and researchers to include more detailed chemistry models in their simulations to better capture the fuels and reactor systems being analyzed.

Application Beyond Engine Design

Zero-RK can tackle a range of problems, from zero- and quasi-dimensional simulations of reactor systems up to full-scale simulations of industrial devices with complex three-dimensional boundaries. Zero-RK also has the ability to perform sensitivity analysis for developing chemical kinetic methods. Examples of its applicability include simulations of fundamental research devices such as shock tubes and rapid compression machines, and commercial applications such as internal combustion engines, gas turbines, rocket engines, and industrial burners.

For the largest system analyzed with Zero-RK, simulation time was reduced tenfold compared to the best competing commercial package. The software also achieved a four-thousandfold reduction in simulation time compared to the best free software alternative. These reductions translate directly to other reactor configurations. As an example, Zero-RK has already been used to develop a rapid compression machine model for Argonne National Laboratory that runs in minutes instead of days.

McNenly sees the potential for Zero-RK to benefit any field in which interaction networks are paramount, including nuclear energy, biological systems, plasma dynamics, and astrophysics. He concludes, “We believe this approach can be helpful to anyone who is looking at what happens when two things collide, when the possibility of that collision is driven by concentrations.”

—Don McNichols

Key Words: chemical reaction, chemical species, combustion engine, computational fluid dynamics (CFD), high-performance computing, sparse adaptive preconditioning (SAP), transportation fuel, Zero-Order Reaction Kinetics (Zero-RK).

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Remarkable Advances in Three-Dimensional Printing

OVER the last decade, additive manufacturing (AM) has burgeoned into a reliable, sought-after capability, enabling rapid prototyping and production of components for automotive, medical, and electronic applications, among others. A variety of techniques is used for AM, in which three-dimensional (3D) structures are built up by sequentially layering one material on top of another in a desired pattern. However, these methods are limited by the size of components they can produce, the scale of component features, or overall production speeds.

A novel 3D printing approach, developed by Livermore engineer Bryan Moran, with support from the Laboratory's Christopher Spadaccini, Julie Jackson, Logan Bekker, Brian Bauman, and Jim Fugina, promises to expand current AM capabilities. Winner of an R&D 100 Award, the Large-Area Projection Microstereolithography (LAP μ SL) system combines the advantages of laser-based stereolithography and digital-light-processing (DLP) stereolithography to quickly and accurately print macroscale products (many centimeters) with highly detailed, microscale features (as small as 10 micrometers).


No other available technology can produce large objects of arbitrary geometries with such small feature size at high speed.

Big Changes in Scale

Moran's creation is a new take on projection stereolithography, wherein ultraviolet (UV) light illuminates a digital photomask that reflects the light and an image of the component to be fabricated through a series of reduction optics onto a photopolymer liquid resin. As the resin cures, it hardens into the shape of the image. DLP-based stereolithography can create features with fine details at high speed, but only over a small area. Conventional stereolithography typically produces larger objects at lower resolution. These size and speed limitations usually result from the way 3D printing machines write the images that the computer generates to physically build an object. "Traditional stereolithography machines require either mechanical stage movement to make large parts (limiting speed and size) or the rastering of laser beams to expose pixels in series (limiting detail and speed)," says Moran. LAP μ SL combines the extraordinary detail and speed inherent to DLP stereolithography with a larger scan area. The machine can produce bigger, more complex objects at a speed of 13.67 cubic centimeters per hour with feature sizes down to 10 micrometers.

LAP μ SL uses a digital micromirror device (DMD) containing several hundred thousand microscopic mirrors arranged in a rectangular array that correspond to the pixels in the image. Each mirror can be set to reflect light onto or out of the system. In this way, the mirrors form the pattern of the image and then project the image onto the build plane. Typically, projection stereolithography systems cast the image onto a single area. The size of this image therefore determines the build area. Larger parts require the build area to be physically moved via mechanical means and are limited by the cost a user is willing to pay for mechanical stages and fixturing.

LAP μ SL's innovative setup eliminates the need for mechanical stage movement. A pair of scanning mirrors moves the

A photograph of Bryan Moran, a middle-aged man with grey hair and a beard, wearing a dark blue button-down shirt and dark trousers. He is standing and smiling at the camera.

Livermore engineer Bryan Moran developed the Large-Area Projection Microstereolithography (LAP μ SL) system.

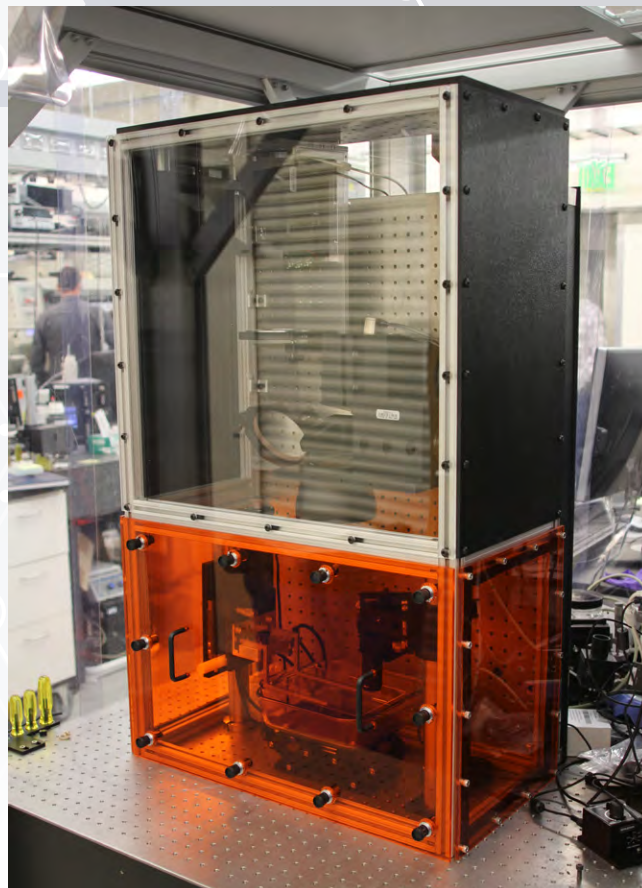
DMD-produced image around a large build area, overlapping and piecing smaller images together like a mosaic. “Instead of having a single static exposure with millions of mirrors, LAP μ SL scans over a wide area, multiplying and overlapping the high-resolution images,” says Moran. When all these “pieces” have been projected into their respective places on the build plane, they create a larger picture with significantly more detail. This mosaic technique is also what makes the device so fast. Spadaccini, the director of the Laboratory’s AM initiative, says, “LAP μ SL is a huge step forward in bringing high resolution and high speed to additive manufacturing.”

Growing Potential

Another benefit of using LAP μ SL is that it is not limited to producing a single large part. “As many parts as can fit on the build plane can be produced at once, making LAP μ SL well suited for higher volume production,” says Moran, whose work was funded by the Defense Advanced Research Projects Agency. (Original work at Livermore on projection microstereolithography was funded by the Laboratory Directed Research and Development Program.) LAP μ SL-produced structures can be used straight out of the system or as templates for additional processing in which the structure is coated with metal, ceramic, or other material. In addition, resin can be removed from a completed structure via chemical means or heat to create extremely light, hollow tube structures.

LAP μ SL is currently only available for customers at the Laboratory and some external collaborators, but the technology has market potential. Moran, who was also presented with a 2015 Federal Laboratory Consortium Outstanding Technology Development Award for LAP μ SL, says the technology has wide-ranging applications. “It can be applied to everything from medical and biotech to structural materials,” he says. “It’s exciting to see how the technology is evolving.”

—Maren Hunsberger



The LAP μ SL system prints three-dimensional centimeter-size products with microscale features (up to 10 micrometers).

Key Words: additive manufacturing, Defense Advanced Research Projects Agency, digital-light-processing (DLP) stereolithography, digital micromirror device (DMD), Federal Laboratory Consortium, Laboratory Directed Research and Development Program, Large-Area Projection Microstereolithography (LAP μ SL), laser-based stereolithography, R&D 100 Award, three-dimensional printing.

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Powerful Laser System Improves Experimental Capabilities

PULSED laser-diode arrays are essential for pumping, or energizing, high-power solid-state lasers for materials processing, defense applications, and scientific exploration. A Livermore team, in partnership with colleagues at Lasertel in Tucson, Arizona, has integrated advances in laser diodes and electrical drivers to develop the High-Power Intelligent Laser Diode System (HILADS). The megawatt-class laser-diode pumping system delivers two-to-threefold improvements in peak output power and intensity over existing technology in a 10-times-smaller footprint.

In the largest deployment of the technology to date, four HILADS devices have been integrated into the Laboratory's High-Repetition-Rate Advanced Petawatt Laser System (HAPLS). (See *S&TR*, January/February 2014, pp. 4–11.) When complete, HAPLS will be the world's highest-average-power petawatt (10^{15} or 1 quadrillion watts) laser. Within HAPLS, the four HILADS devices produced 3.2 megawatts of peak optical power at a repetition rate of 20 hertz (20 repetitions per second), making it the highest-peak-power laser-diode array in the world.

The Power of Innovation

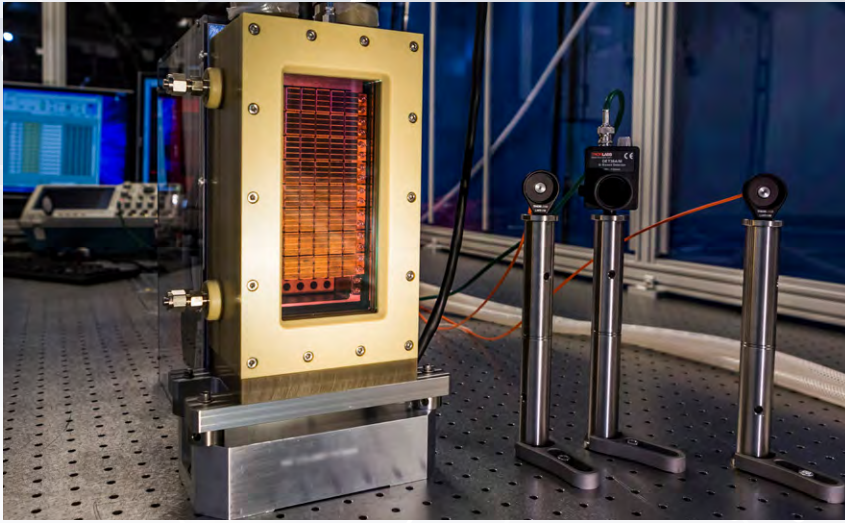
Ultrahigh-energy laser systems, like petawatt-class lasers, require diode-array pumps that emit megawatt pulses, frequencies of at least 10 hertz, and high brightness (a combination of power and high beam quality). Until HILADS,

a number of engineering challenges prevented development of such powerful and intense laser-diode pumping systems. Those challenges centered on integrating the design and assembly of multiple components: remotely located, higher power current drivers; larger stacks of diodes; optics capable of collimating (aligning) the output of the many diode chips in the stack; and a smaller footprint to save space on often-crowded laser tables that are typically placed in clean rooms where space is at a premium. Plus, minimum stress had to be placed on the diode chips to ensure their reliability over billions of pulses.

HILADS integrates a high-density diode array with an electronic driver and a control system to improve performance. The two-dimensional diode array uses diode stacks mounted on a backplane to provide cooling and mechanical alignment. Each diode stack contains 40 laser-diode chips soldered between thermally conductive metal spacers to minimize stress. Monolithic microlens arrays collimate each stack's output to maximize brightness. Specialized cables connect the array to the driver. Because of its modular design, HILADS can scale

Development team for the High-Power Intelligent Laser Diode System (HILADS): (back row, from left) Glenn Beer, Ken Charron, Paul Rosso, Chuck Heinbockel, Brian Heidl, Andy Bayramian, Dan Mason, Ed Koh, and Tara Silva; (front row, from left) Steve Fulkerson, Constantin Haefner, Steve Pratuch, Bob Deri, Carlene Kiker, Steve Telford, Jeff Horner, and Jeff Jarboe.





HILADS can produce 3.2 megawatts of peak optical power, making it the highest-peak-power diode array in the world. Shown here is one of the system's laser-diode arrays, which contains 40-diode-chip stacks arranged in an 8-by-5-channel configuration.

to larger arrays and power levels without compromising its intensity or brightness.

The HILADS two-to-threefold increase in peak optical intensity was made possible by two key innovations. The first was a novel design approach for the diode chips and their package that enables the chips to operate at higher output power while being located closer to neighboring chips. These two factors require higher efficiency and improved thermal management to avoid overheating the devices. Each HILADS stack contains 40 laser diodes and measures just 11 by 17 square millimeters—the size of a Forever postage stamp, but thicker. The diode is capable of producing greater than 500 watts of peak output power, for a total of 20 kilowatts per stack.

The second innovation was a single-optic microlens array that collimates the output of all 40 chips in a stack to increase intensity. Traditional techniques to achieve good alignment use a longer lens focal length, which can degrade the peak optical intensity of the stack. HILADS uses a custom process to rapidly map the position of every emitter on each of the 40 chips to submicrometer precision. The information is used to fabricate a single optic that contains a monolithic array of microlenses covering the entire stack. In addition to the excellent collimation it provides, the single-optic monolithic microlens array requires only one alignment step, thus significantly reducing related labor costs.

Another important advantage of HILADS comes from its compact electronics and unified, self-monitoring system interface. The HILADS controller is two times smaller than alternative solutions and can be scaled to much higher power levels. The controller chassis is small enough to be mounted below the laser table and generates no thermal air currents that would interfere with laser operations. In addition, 10-meter-long cables connecting the array and driver allow the electronics to be

kept at a distance from the laser table, saving space in the clean room that houses the equipment.

A Bright Horizon for HILADS

The features and advantages of HILADS have been demonstrated in deployment on HAPLS, now under development at the Laboratory for installation in the European Union's Extreme Light Infrastructure (ELI) Beamlines facility in the Czech Republic, the world's new preeminent laser-science research facility. A key component of HAPLS, HILADS has proven extremely stable. Extensive testing of the diode stacks indicates that HILADS's lifetime will exceed 2 billion pulses.

The ELI Beamlines initiative will use high-energy diode-pumped lasers to explore light-material interactions. Once the HILADS-pumped HAPLS is installed at the facility, it will ultimately generate a peak power greater than 1 petawatt, with each pulse delivering 30 joules of energy in less than 30 femtoseconds (trillionths of a second)—the time it takes light to travel a fraction of the width of a human hair—at a repetition rate of 10 hertz. HILADS will find a bright future as part of HAPLS, which will make possible many new applications in physics, medicine, biology, and materials science. In addition, the technology will contribute to the development of laser-driven fusion power plants.

—Malone Locke

Key Words: electronic driver, Extreme Light Infrastructure (ELI) Beamlines facility, High-Power Intelligent Laser Diode System (HILADS), High-Repetition-Rate Advanced Petawatt Laser System (HAPLS), laser, pulsed-diode array, R&D 100 Award.

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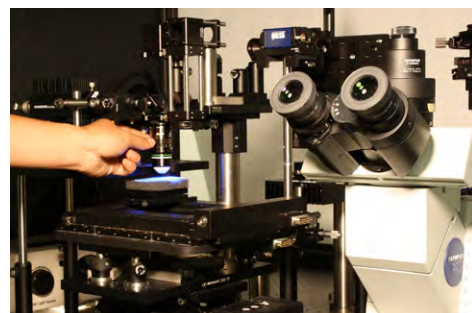
R&D 100 Award Finalists Support Laboratory Missions

LAURENCE Livermore is home to researchers from diverse disciplines, including physical and life sciences and engineering, who push the state of the art in their respective fields to support the Laboratory's many missions. This year, three notable Livermore teams were chosen as finalists and runners-up in *R&D Magazine's* annual competition that recognizes top scientific and engineering products and technologies with commercial potential.

Each of these teams innovated existing technologies to create novel tools. Previous research into microelectromechanical systems- (MEMS-) based adaptive optics (AO) led to development of an advanced confocal microscope for viewing detailed cellular-level structures. Another technology builds on radio-frequency identification (RFID) to produce a system for faster, more efficient tracking of emergency equipment in harsh environments. Finally, researchers in the National Ignition Facility (NIF) improved x-ray framing camera technology to deliver a diagnostic that achieves unprecedented temporal resolution for laser experiments.

A Clearer View of Living Structures

Since its invention in the late 16th century, the microscope has been an important tool for observing and analyzing biological structures, but each type has some limitations. For example,



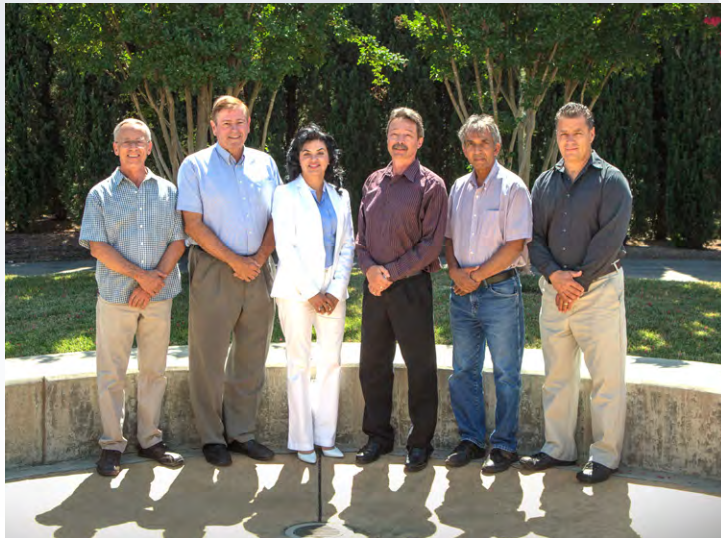
(above) The Microelectromechanical Systems- (MEMS-) Based Adaptive-Optics Confocal Microscope (MAOCM) combines adaptive optics and confocal microscopy to produce high-resolution, three-dimensional images of living tissue at the cellular level. (right) Livermore codevelopers of MAOCM: (from left) Diana Chen and Scott Olivier.



compound and dissection microscopes offer different degrees of magnification but with similar resolution. Scanning electron and transmission electron microscopes provide higher resolution, but the samples have to be specially prepared using electrically conductive material and must be mounted on metal grids and observed in a vacuum, which prevents observation of a living specimen. The confocal microscope was a major advance over existing technologies for analyzing live tissue, enabling three-dimensional (3D) image reconstruction of a thick sample. However, optical aberrations created by the sample's inhomogeneous refractive index still limit the instrument's overall resolution.

Developed in collaboration with academic and industrial partners, Livermore's innovative MEMS-based AO Confocal Microscope (MAOCM) leverages the latest advances in MEMS and AO technology to enable high-resolution, 3D views of complex living tissues at the cellular level. The instrument uses the same AO principles employed in the world's largest telescopes to provide clearer images of distant astronomical objects. An AO deformable mirror integrated into the device provides real-time correction of aberrations in both the illumination and imaging light paths to remove image distortions, thus enabling high-resolution, 3D live images to be viewed immediately by scientists or clinicians. AO compensates for optical aberrations by controlling the phase of the light waves, or wavefronts, that distort the light and degrade the final image. MAOCM automatically measures the optical aberrations in the light path with a wavefront sensor and then rapidly compensates for these aberrations with a wavefront corrector.

Biologists from the University of California at Santa Cruz used MAOCM to image *in vivo* fly embryos. MAOCM's penetration depth was tested by performing AO correction from the top surface of a sample to a depth of 100 micrometers. Prior to wavefront correction, cell centrosomes could only be observed down to 60 micrometers. After correction, they could be observed to 95 micrometers. The size of the point-spread function, which



(left) Development team for the Smart Real-Time Inventory System Based on Long-Range, Battery-Free, Radio Frequency Harsh Environment Tag (HET) system: (from left) Del Ekels, Rick Twogood, Faranak Nekoogar, Dave Weirup, Farid Dowla, and Don Mendonsa. (Not pictured: Jimmie Jessup.) (above) The HET system enables first responders to quickly and more efficiently track inventories of emergency equipment while working in harsh environments.

defines image resolution, showed an approximate eight times improvement over a conventional confocal microscope. The Strehl ratio, which measures the image quality, calculated more than 20 times improvement.

Purchased as a lower cost add-on or as a complete system, the MAOCM instrument enables unprecedented visualization of cellular content and cell-cell interactions in deep tissue for fundamental scientific research and clinical processes. Chen says, "This technology will enable earlier detection of diseases and provide more effective monitoring of disease progression and treatment."

Inventory Tracking for First Responders

When it comes to responding to a critical situation, emergency response teams require quick, efficient methods for tracking extensive equipment inventories. Manual systems can be slow and unreliable, prone to errors, omissions, and outdated information. Inventory systems that use RFID enable faster, more reliable tracking, but these systems typically have short lifetimes, maintenance issues, limited detection ranges, and poor performance in harsh environments. Thus, they are unsuitable for first responder purposes.

Researchers at Lawrence Livermore and Dirac Solutions, Inc., developed the Smart Real-Time Inventory System Based on Long-Range, Battery-Free, Radio Frequency Harsh Environment Tag (HET) system to remedy these issues. The automated inventory tracking system uses novel passive RF tags, specialized portal or handheld readers, and a customized, cloud-based database to provide time-sensitive and real-time inventory or personnel tracking in environments that are hostile to RF signals.

The RF tags used in the HET system are battery-free, so they have an indefinite lifetime. These tags can be placed into inventory items or carried in clothing for personnel tracking. Much like a mirror reflects light, the tags—which range in size from a postage stamp to a standard printed photo—receive their energy from radio waves transmitted either from a stationary reader antenna or from a

handheld reader. The larger the tag, the greater the reading distance, up to approximately 60 meters for a 10-by-15-centimeter tag. HET multistatic, distributed reader antennas focus low-power RF signals onto confined monitoring areas to provide complete coverage of the tags. Multiple reader antennas are used to coherently focus the electromagnetic beam from various directions to see objects in cluttered and obscured environments. A smart, multilayered, cloud-based database allows real-time inventory data to be available from both handheld and portal readers.

Currently, response teams manually check their equipment before and after responding to an event. According to Livermore's Faranak Nekoogar, who helped develop the HET system, "Manual inventory can take hours to complete. With the HET system, RFID tags provide accurate, automatic inventory control that can be verified in seconds." For routine inventory processing, operators can use handheld readers as they look through the equipment to detect individual tags and update the cloud database. During an emergency response situation, individual tagged items inside transportation cases can be quickly packed into a vehicle and then detected by portal readers, reporting the inventory in real time as the vehicle passes.

The HET system is the only passive RFID inventory system designed for emergency responders. The system has been deployed in nuclear emergency response centers, where it has already improved operational efficiency and reliability. In the future, the HET system may find application in inventory control for other government agencies, medical and fire emergency response teams, and personnel tracking during search-and-rescue missions.

World's Fastest X-Ray Camera

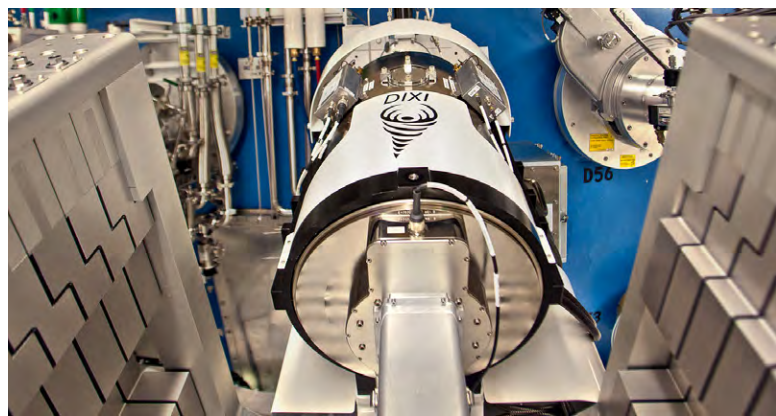
NIF provides scientists with a platform to research nuclear weapons physics and to explore basic science, such as astrophysical phenomena, materials science, and nuclear science. To support these efforts, NIF requires advanced diagnostics to accurately record experimental results. One of these technologies, the Dilation X-Ray Imager (DIXI), records two-dimensional x-ray images

with unprecedented temporal resolution—the timescale over which changes in size or position can be measured—making it the world’s fastest x-ray framing camera. The instrument was developed by Livermore in collaboration with General Atomics and Kentech Instruments, Ltd.

DIXI leverages three established technologies to improve its functionality in a harsh environment as well as its temporal resolution. These components include a pulsed transmission photocathode that converts incoming x-ray signals into electrons, a magnetic field for guiding the electrons in the drift space, and a standard framing camera backend to amplify a section of the dilated electron signal and record the images. DIXI also employs additional shielding to protect the recording device from x-ray and neutron-induced background signals.

The instrument uses pulse dilation (or stretching of the electron signal) to achieve a temporal resolution 10 times faster than traditional x-ray framing cameras. A voltage ramp imparts a velocity gradient on the signal-bearing electrons that are generated when x rays hit the transmission photocathode. As the electron signal traverses a drift space, it is stretched out in time, resulting in a signal that is 50 times longer. The high temporal resolution is achieved by selecting only a small part of the stretched signal stream for amplification and detection. Imaging enhancements result in the capability to resolve changes as fast as 5 trillionths of a second, equivalent to 200 billion images per second.

In addition, DIXI can survive 10 times higher neutron backgrounds compared to existing technologies. A longitudinal magnetic field guides the electrons within the drift space, allowing the instrument to be tilted off-axis to the object being viewed, which in turn permits additional shielding.



As the world’s fastest two-dimensional framing camera, DIXI can produce images of an imploding target capsule with 10 times faster temporal resolution and in environments with 10 times higher neutron yields than its competitors.

“DIXI is well suited for detecting x-ray emissions produced by various mechanisms, including those from inertial confinement fusion implosions and laser–plasma interactions,” says Livermore’s Sabrina Nagel, who helped develop the instrument. “The imaging system’s greater-than-50-times magnification allows resolution of the very small emissions from compressed NIF target capsules. This instrument has already captured details of NIF implosions never before seen with slower, traditional framing cameras.”

The success of DIXI at NIF has already sparked interest in adapting its pulse-dilation technology to other applications such as time-resolved neutron spectra. The system is also transportable and has variable temporal resolution and record length, which makes it a desirable diagnostic for other high-power laser facilities and x-ray emitting machines.

DIXI, MAOCM, and the HET system are three examples of how Laboratory researchers push the boundaries of scientific innovation and build on past technologies to improve capabilities. As evidenced by these three innovations, Laboratory researchers continue to advance the state of the art in the areas of cell biology, emergency response, and laser diagnostics in support of Livermore’s national security mission.

—Lanie L. Rivera

Key Words: adaptive optics (AO); Dilation X-ray Imager (DIXI); disease; emergency response; inventory; microelectromechanical systems (MEMS); MEMS-Based Adaptive Optics Confocal Microscope (MAOCM); National Ignition Facility (NIF); optics; pulse dilation; R&D 100 Award; radio frequency; Smart Real-Time Inventory System Based on Long-Range, Battery-Free, Radio Frequency Harsh Environment Tag (HET) system; x-ray framing camera.

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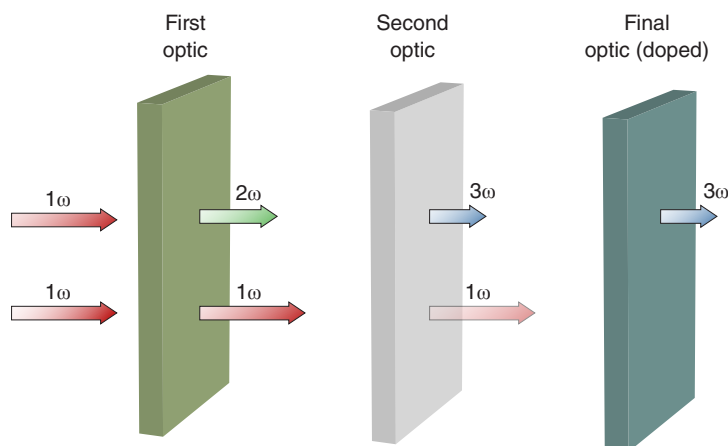
Development team for the Dilation X-Ray Imager (DIXI): (from left) Joe Holder, Jacob Parker, Charles Brown, Jay Ayers, Perry Bell, David Bradley, Sabrina Nagel, Joseph Kilkeny, and Kenneth Piston. (Not pictured: Walter Ferguson and Brian Felker.)

Fine-Tuning a LASER BEAM

This artist's rendering depicts a beam of light being absorbed by a dopant molecule. (Rendering by Brandon Wood and Roger Qiu.)

EXPERIMENTS at Livermore's National Ignition Facility (NIF) explore high-energy-density regimes and yield groundbreaking results that contribute to basic science and national security. Toward this end, researchers continue to improve experimental parameters, including data recovery, target design, and beam quality. Technological advancements include improved diagnostic capabilities; alternative shapes for target casings, called hohlraums; and recently, development of chemically doped glass optics—those enhanced with other elements—for fine-tuning the frequency of a laser beam.

During a NIF experiment, laser light begins in the infrared, with a characteristic frequency (1,053 nanometers) that researchers refer to as 1-omega light. As it travels down the beam path, the light frequency is doubled into 2-omega (527-nanometer), visible green light and finally tripled into 3-omega (351-nanometer), ultraviolet light before engaging the target. (See *S&TR*, April/May 2010, pp. 4–11). A series of specialized optics is responsible for this light transformation. Unfortunately, conversion efficiency is not perfect, leaving unconverted light mostly in the 1-omega frequency. As a result, some 1-omega light becomes



At the National Ignition Facility, a series of optics along the beam path filter and convert 1-omega (1ω), infrared and 2-omega (2ω), visible light into 3-omega (3ω), ultraviolet light. Doped glass could be used as the final optic for filtering or converting any residual 1ω light before the laser beam reaches the target.

mixed with the 3-omega light and can have undesirable effects on experiments as well as the laser system. For example, 1-omega light can interact with the plasma produced during laser–target interactions in ways that hinder symmetrical compression of the target. This light can also reflect back up the beam line, potentially damaging optical components.

One of the challenging goals of physicists and engineers at NIF is to develop glass for optics that can absorb as much infrared light as possible, fully transmit all the ultraviolet light, resist damage, and be feasibly manufactured. Doped glass could serve as an effective mechanism for ensuring only ultraviolet light reaches the target. While the laser-physics community generally accepts that doped glass may be useful in developing new types of optics, Livermore researchers have taken that theory one step further, demonstrating a correlation between the frequency and intensity of absorbed light and how dopants alter that absorption.

A World of Color

In 2011, a Livermore team including Brandon Wood, Roger Qiu, Kathleen Schaffers, Paul Ehrmann, Stavros Demos, Philip Miller, Tayyab Suratwala, and Richard Brow began a series of glass-doping studies. The goal of the research—part of a three-year project funded by the Laboratory Directed Research and Development (LDRD) Program—was to understand how to make the best glass for absorbing unwanted light while efficiently transmitting 3-omega light. “Every plant that looks green, everything in the world that displays a color, is absorbing certain wavelengths of light and letting others through,” says Wood, the theory lead. “This light absorption is happening on a molecular level.”

Many of the molecules most commonly found in nature that absorb light and subsequently generate color contain transition-metal ions, such as iron and copper. Explains Wood, “When an isolated copper or iron atom is excited by low-energy photons, such as 1-omega light, it usually won’t do much of anything. For a change in energy state to occur and for an infrared photon to be absorbed, the metal needs to be complexed with another molecule that binds to it, called a ligand.” The combination of the metal and the ligand is called a coordination compound. During

the study, the team looked at all the optical absorption properties of potential dopants, including the wavelengths of light that a compound absorbs, the intensity of the absorption profiles (amount of light), and the absorption breadth (frequency range).

The iron and copper ions in these compounds have an outermost shell of electrons whose energies are subtly changed by the presence of ligands, with some electrons shifting to higher energies and others to lower energies. When the molecule absorbs a photon of the right frequency, electrons can jump between the lower and higher energy states. In keeping with the law of conservation of energy, the energy difference between the electrons’ original state and their excited state is equal to the energy of the absorbed photon. The difference is also inversely related to the wavelengths of the light. Only the wavelengths matching the energy difference can be absorbed, so the compound appears as the appropriate complementary colors—the sum total of all the wavelengths that cannot be absorbed. Because iron and copper complexes can absorb infrared light, the research team considered them the top candidates for their project and set out to find the best ligands for creating the most effective coordination compound.

Bridging the Gaps in Theory

The arrangement of electrons in a ligand dictates how much and what kind of light it can absorb. An area of study called ligand field theory has explored the properties of different ligands since the 1930s. As defined by the theory, a “weaker” ligand creates a complex that has a smaller difference in energy between ground and excited states, allowing the ligand to absorb lower frequency light. “Stronger” ligands have a larger energy difference between ground and excited states and can therefore absorb light of higher frequencies. “The terms ‘strong’ and ‘weak’ are pretty amorphous,” says Wood. “The theory doesn’t tell us much about why some ligands are weak and some are strong.” Qiu, the experiment lead, agrees, saying, “Ligand field theory does not indicate correlations between the absorption intensity, breadth, and energy (or wavelength). Our experiments were designed to improve our understanding of those qualities.”

Wood ran a series of computationally intensive first-principles molecular dynamics simulations for 10 dopant ions on the Laboratory’s Cab supercomputer. These simulations probed the dopants’ behavior in aqueous solutions under varying conditions, such as different temperatures and pressures, and in different complex configurations. Meanwhile, Qiu tested these same solutions experimentally. “Solutions are much cheaper, easier, and faster to prepare than glasses,” says Qiu. “Some of the strong and weak ligands have been identified by ligand field theory and are readily available, which enabled us to carefully select the relevant ligands for our physical experiments.”

By comparing the results of the simulations and the experiments, the researchers could better determine absorption properties and pinpoint absorption mechanisms for dopants. “In our experiments, we had to be careful about making assumptions,” says Wood. “We



Aqueous solutions made from different coordination compounds display their varying absorption capabilities through color.



Livermore researchers (from left to right) Kathleen Schaffers, Paul Ehrmann, and Roger Qiu observe the infrared-blocking properties of various dopants in aqueous solutions.

couldn't assume that every ion complexes with the same ligand in the same way, or that every ion complexes with the identical number of ligands. We used simulations to look at the aqueous solutions in a much more controlled way to see which of our assumptions could hold true."

Whereas ligand field theory focuses only on the frequency of absorption, the team's results physically demonstrate that absorption intensity and probability of absorption (also called oscillator strength) display patterns, with the strongest and weakest ligands having the best outcomes. The simulations revealed that these correlations are actually the combined result of several effects, and that they depend on the identity of the ligand as well as how the coordination compound responds to fluctuating conditions in the liquid. Wood says, "We've shown that conventional interpretations based on ligand field theory alone are insufficient for capturing the full characteristics of the absorption profile." The team was also successful in identifying the most desirable copper and iron coordination compounds that may produce an effective infrared-blocking optic for NIF applications.

From Optics to Windows

The team's next step is to have optics manufactured with the correct properties. The aqueous tests allowed the team to observe the coordination compounds in multiple conformations, or spatial arrangements, based on certain environmental factors, including temperature. Kathleen Schaffers, the project's principal investigator, explains, "Glass is an interesting state of matter—it's essentially a slow-moving liquid, something between a liquid, a solid, and a

crystal. We can engineer glass to have certain properties, including the ability to hold a molecule in a specific conformation. Our ultimate goal is to develop concrete recommendations so that glass can be engineered with those properties."

While doped glass could one day help improve light frequency conversion for experiments at NIF, it may also have applications outside the Laboratory. Qiu notes, "Our research could be applied to develop energy-efficient 'smart' windows for commercial and industrial use." A large portion of the solar spectrum that reaches Earth's surface is in the infrared range and produces heat, so doped windows could be useful in environmentally conscious design—filtering out heat and radiation while letting in visible light. In addition, the team's research could lead to a deeper understanding of how light is absorbed by organisms in nature, a field called photobiology. Through greater understanding of how doped glasses can improve light absorption, the team has taken a step forward in developing better optics for scientific research and more efficient glass for a wide range of applications.

—Maren Hunsberger

Key Words: absorption, absorption profile, aqueous solution, Cab supercomputer, complex, coordination compound, dopant, doped glass, infrared light, laser, Laboratory Directed Research and Development (LDRD) Program, ligand, ligand field theory, National Ignition Facility (NIF), optics, ultraviolet light, visible light.

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Patents and Awards

In this section, we list recent patents issued to and awards received by Laboratory employees. Our goal is to showcase the distinguished scientific and technical achievements of our employees as well as to indicate the scale and scope of the work done at the Laboratory. For the full text of a patent, enter the seven-digit number in the search box at the U.S. Patent and Trademark Office's website (<http://www.uspto.gov>).

Patents

High-Density Percutaneous Chronic Connector for Neural Prosthetics

Kedar G. Shah, William J. Bennett, Satinderpall S. Pannu

U.S. Patent 9,138,571 B2

September 22, 2015

Compact Optical Transconductance Varistor

Stephen Sampayan

U.S. Patent 9,142,339 B2

September 22, 2015

Passive Chip-based Droplet Sorting

Neil Reginald Beer, Abraham P. Lee, Andrew C. Hatch, Jeffrey S. Fisher

U.S. Patent 9,174,213 B2

November 3, 2015

Electrostatic Stabilizer for a Passive Magnetic Bearing System

Richard F. Post

U.S. Patent 9,197,110 B2

November 24, 2015

Awards

John S. Foster, Jr., became the first recipient of the **John S. Foster, Jr. Medal** on September 29, 2015. Established by Lawrence Livermore National Security, LLC, and bestowed on an annual basis by the director of **Lawrence Livermore National Laboratory**, the medal recognizes an individual for exceptional leadership in scientific, technical, and engineering development and policy formulation in support of U.S. nuclear security objectives.

Foster began his career at the newly formed Lawrence Livermore National Laboratory after earning his degree from the University of California at Berkeley. While at Livermore, he led a team that made a major breakthrough in nuclear weapons design that continues to be the basis for all modern U.S. nuclear weapons. He also recognized the need for safety and security features in deployed nuclear weapons and spearheaded early development and improvement efforts. He became Livermore's director in 1961. In this role, he drove Livermore to expand its national security responsibilities to meet existing and emerging needs.

Foster subsequently served eight years as director of Defense Research and Engineering for the Department of Defense until 1973, when he left to become the vice president of TRW, Inc. He later served as TRW's officer for Science and Technology and joined the board of directors. Foster has served on many defense-related advisory committees and task forces, including as a member of the Defense Science Board for more than three decades as well as of the President's Foreign Intelligence Advisory Board, and was a member of the recent Congressional Commission on the Strategic Posture of the United States.

Livermore climate scientist **David Bader** has been elected a fellow of the **American Meteorological Society (AMS)**. Election to the grade of AMS fellow recognizes outstanding contributions to the advancement of atmospheric and related sciences, technologies, applications, and services for the benefit of society. Bader began his career in 1985 at Pacific Northwest National Laboratory. He later moved to Lawrence Livermore in 2003 as director of the Program for Climate Model Diagnosis and Intercomparison. In 2009, he took a position at Oak Ridge National Laboratory as the founding deputy director of the Climate Change Science Institute. He returned to Livermore in 2011 as climate program leader. Bader has been a member of AMS for more than 20 years and has held positions

on the AMS Applied Climatology Committee, the AMS Board on Data Stewardship, and program committees for several AMS conferences. A maximum of 0.2 percent of the AMS membership is approved annually through the fellow nomination process.

Seven Lawrence Livermore scientists have been selected as fellows of the **American Physical Society (APS)**. **Lee Bernstein** was cited by the Division of Nuclear Physics for "work developing novel methods of determining neutron–nucleus cross sections via high-resolution gamma-ray spectroscopy, the early development of surrogate ratio method, and the study of nuclear processes in high-energy-density plasmas at NIF." **Stavros Demos** was recognized by the Division of Atomic, Molecular, and Optical Physics for "outstanding contributions using unique optical techniques to understand the relaxation dynamics of point defects and developing noninvasive biomedical photonics for rapid tissue assessment."

Fred Streitz was selected by the Division of Computational Physics for "important contributions to computational condensed matter physics and for leadership in extreme scale computation."

The Division of Plasma Physics honored three researchers. **Pierre Michel** was cited for "outstanding contributions to laser–plasma interaction physics and dynamic multi-laser beam physics, enabling symmetry control in indirectly driven inertial confinement fusion implosions." **Yuan Ping** was named for "pioneering experiments exploring the nature, equilibration, and use of nonequilibrium plasmas strongly driven by coherent and incoherent sources." **Vladimir Smalyuk** was recognized for "seminal contributions to the understanding of hydrodynamic instabilities in inertial confinement fusion using elegant experiments on Omega and NIF."

Finally, **Damian Swift** was cited by the Topical Group on Shock Compression of Condensed Matter for "wide-ranging contributions to shock- and ramp-wave compression experiments using laser, pulsed-power, and explosive drivers, and for employing rigorous quantum and statistical mechanical principles to guide the formulation of theoretical solutions to experimental problems."

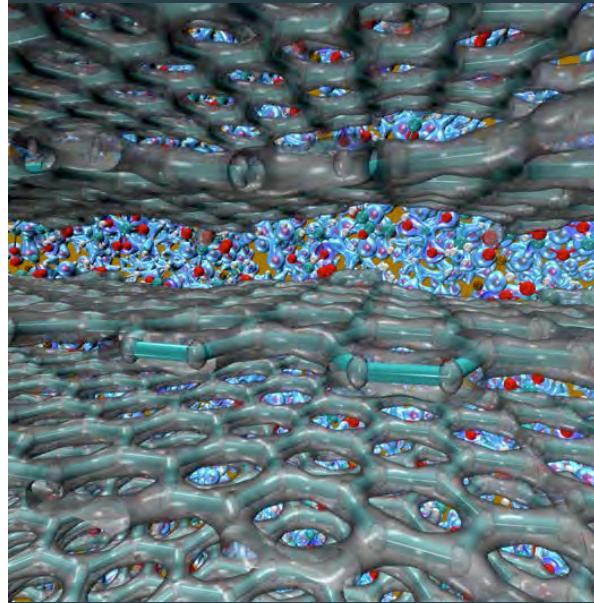
Election to APS fellowship is limited to no more than one half of 1 percent of APS' membership for a given year. In the past 30 years, more than 100 Lawrence Livermore scientists have been elected APS fellows.

A Growing Family of Targets for the National Ignition Facility

The National Ignition Facility (NIF) was designed to develop a deeper understanding of the behavior of materials at extreme pressures and temperatures. The world's most energetic laser, NIF is the paramount experimental facility in the National Nuclear Security Administration's Stockpile Stewardship Program. NIF's millimeter-scale targets, combined with associated laser pulse shapes and a vast array of diagnostics (together called a platform), also make possible breakthrough research in inertial confinement fusion; high-energy-density physics; and discovery science, which includes astrophysics and materials science. NIF experiments rely on a wide variety of targets, all of which have intricate assemblies of extremely small parts. Designing, machining, and assembling these parts with micromanipulators into precisely manufactured targets requires a complex interplay among target designers, physicists, materials scientists, chemists, engineers, and technicians. The small-scale phenomena and extreme conditions targets encounter during experiments make the results highly susceptible to any manufacturing imperfections. Many fabrication techniques, materials, and tools are derived from industry, while new fabrication, measurement, handling, and inspection techniques are developed in-house.

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Understanding Materials at the Nanoscale



Livermore researchers are designing and fabricating new materials with novel structures, functions, and properties.

Also in March

- *Using three-dimensional bioprinters, Laboratory scientists are engineering tissue patches with vascular networks for toxicological and medical applications.*
- *New isotopic methods are helping characterize and protect California's groundwater.*
- *An odd class of materials that acts as both conductors and insulators could be the key to faster, cheaper, more energy-efficient electronics.*

Science & Technology Review
Lawrence Livermore National Laboratory
P.O. Box 808, L-664
Livermore, California 94551

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